Blazed Transmission Gratings for Constellation-X: EUV and Soft X-Ray Results

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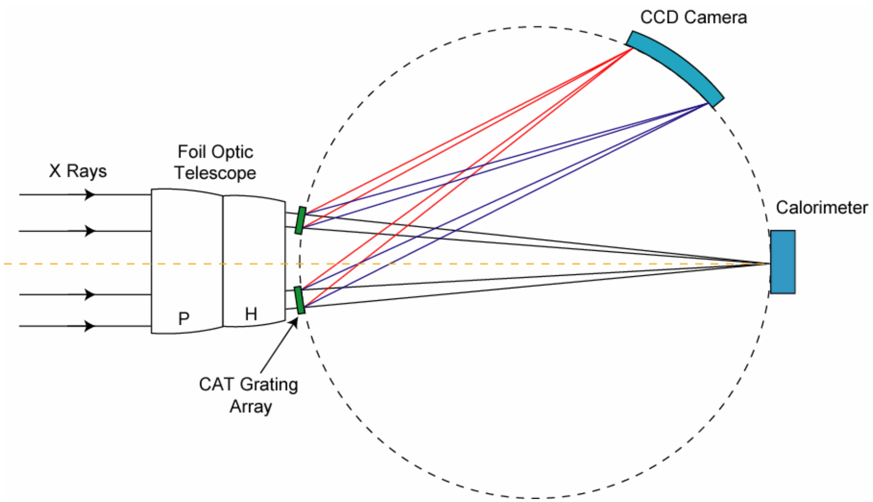
MIT Kavli Institute
for Astrophysics
and Space Research

Con-X CAT (Critical-Angle Transmission) Grating Spectrometer

Con-X requirements for effective area and resolution below 0.6 keV are met and exceeded by CATGS (Flanagan *et al*., Dec.'06 FST and Proc. SPIE **6688**, 66880Y (2007))



- High efficiency blazed CAT gratings

- High resolving power (R=E/ΔE > 2000 (HEW) below 1.2 keV) due to high dispersion (10,000 lines/mm) and sub-aperturing

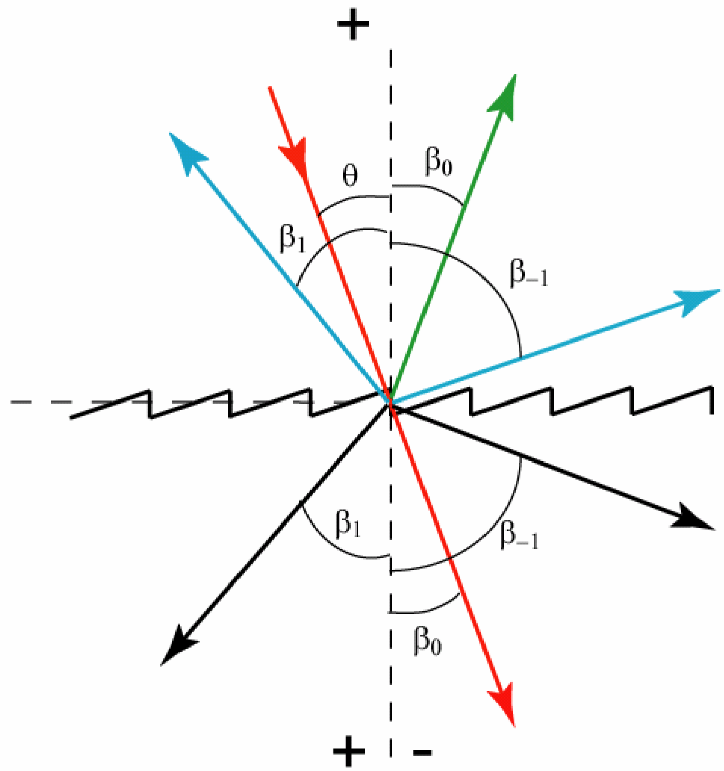
- High energy x-rays go to calorimeter at the telescope focus

- Effective area down to 165 eV

- Low mass (< 61 kg, incl. CCDs & electronics)

- Easy alignment tolerances (up to $(m\lambda/p)^{-2} \sim 10^3$-$10^4$ times better than reflection grating)

Alignment sensitivity: Transmission Grating vs. Reflection Grating



$$m\lambda/p = \sin\theta - \sin\beta_m$$

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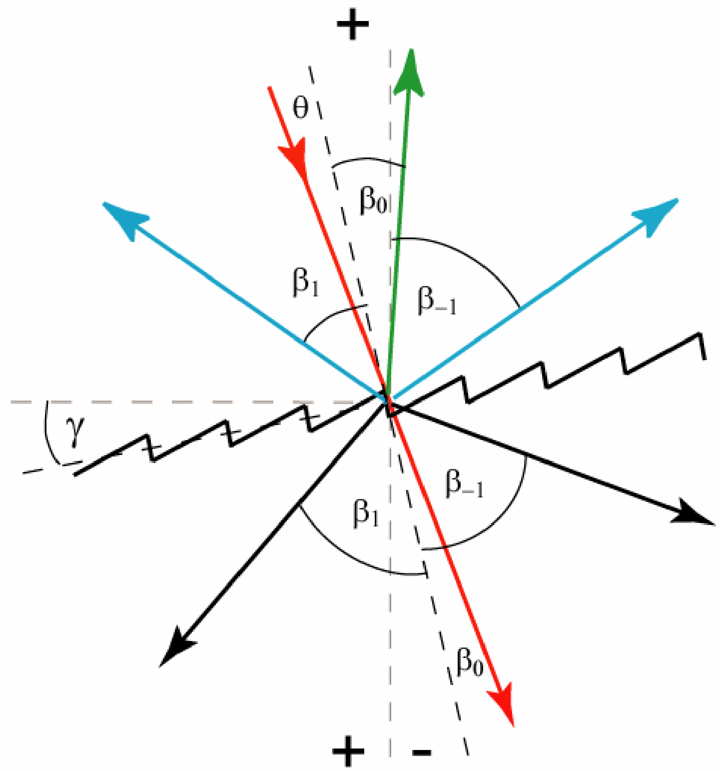
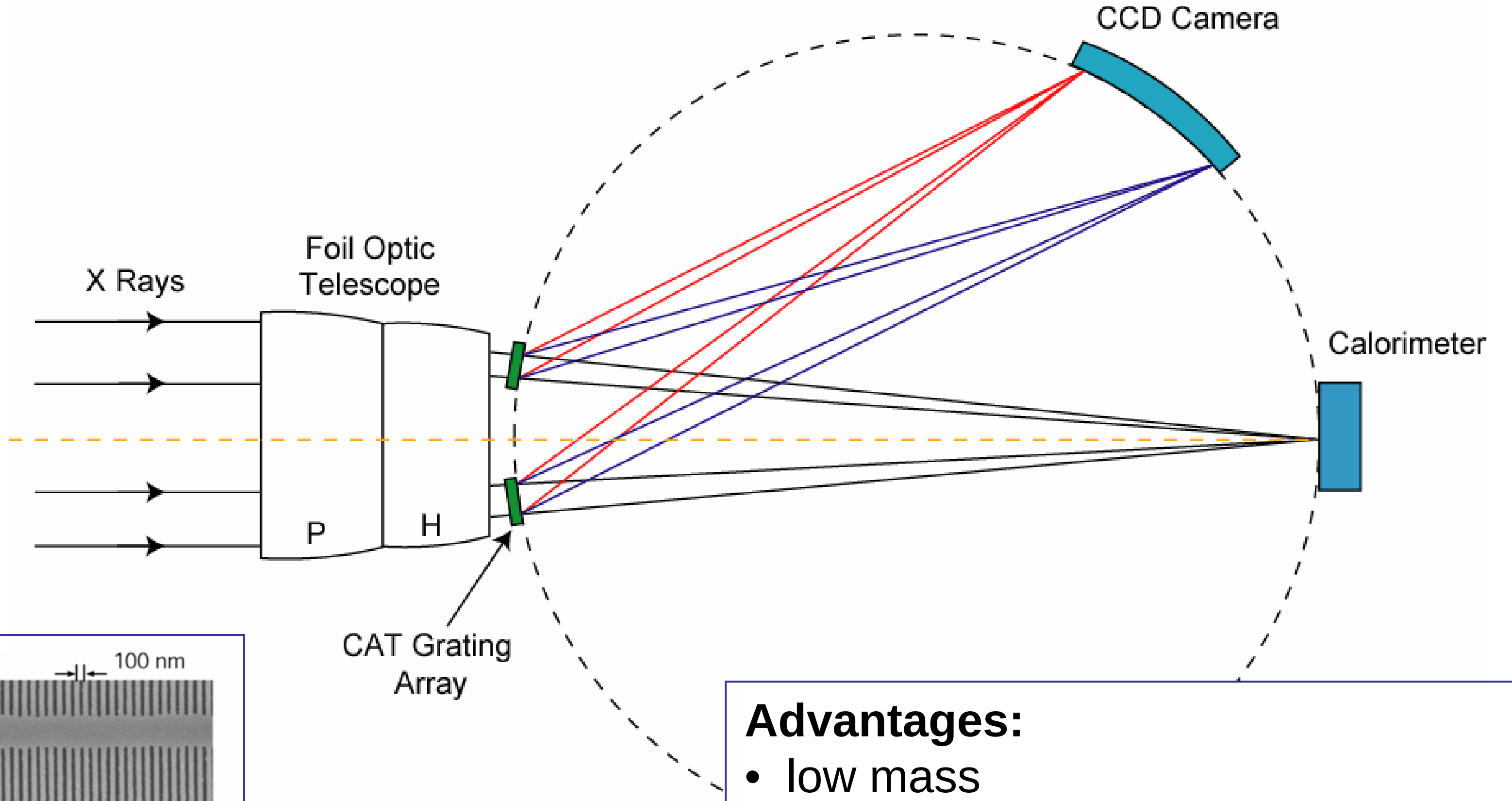
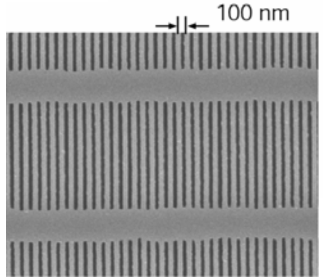
Alignment sensitivity: Transmission Grating vs. Reflection Grating



$$m\lambda/p = \sin\theta - \sin\beta_m$$

Con-X CAT (Critical-Angle Transmission) Grating Spectrometer Concept





10,000 l/mm transmission grating

Advantages:

- low mass
- relaxed assembly tolerances
- high diffraction efficiency
- up to 4X dispersion of Chandra HETGS
- no pos. orders (i.e., smaller detector)

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Con-X Critical-Angle Transmission Grating Spectrometer Layout

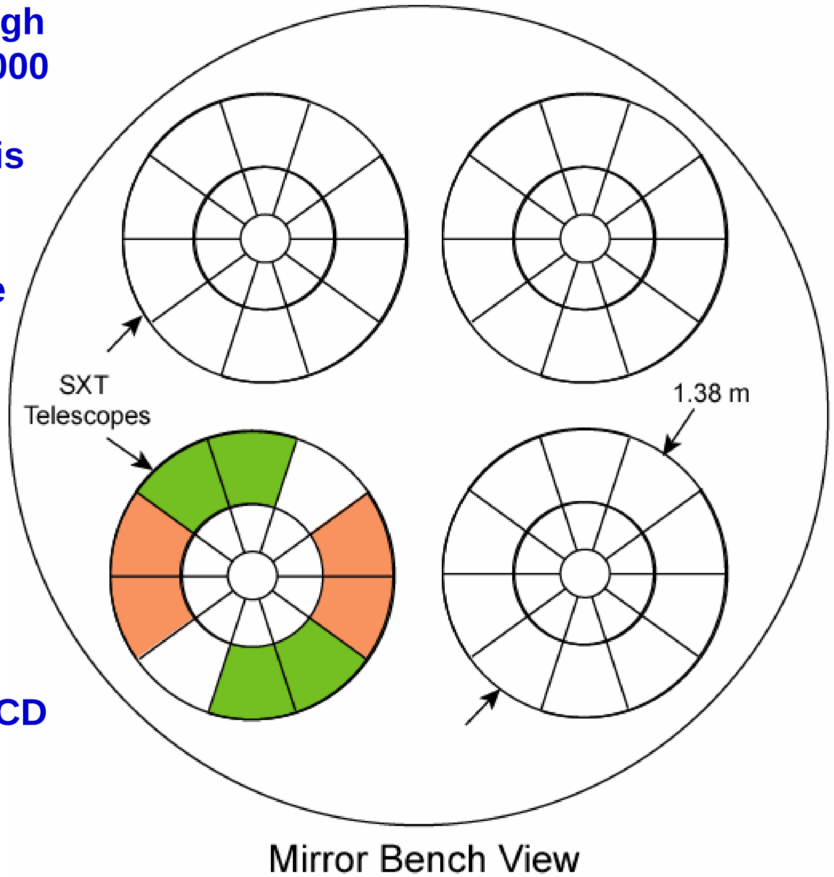
Two grating arrays are mounted on only one SXT. Each array has its own readout. The other 3 SXTs are unaffected.

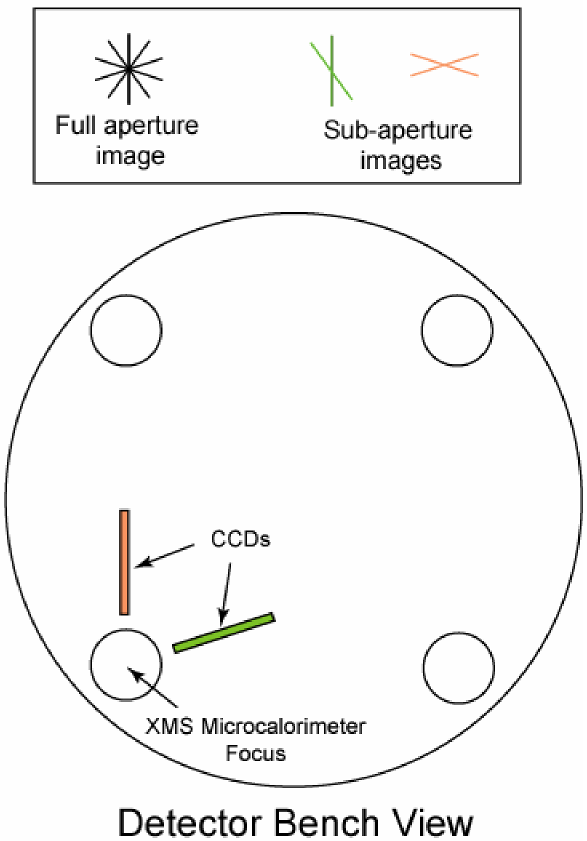
Covers outer annulus R=324 mm to 659 mm. Shells inward of the mirror gap are not covered to preserve high-energy throughput to the XMS.

Gratings have high line density (10,000 l/mm) and are blazed: readout is compact and cleanly outside of XMS envelope

Readout range: mλ=25 Å to 77 Å

Length 488 mm covered by 20 CCD devices (each)





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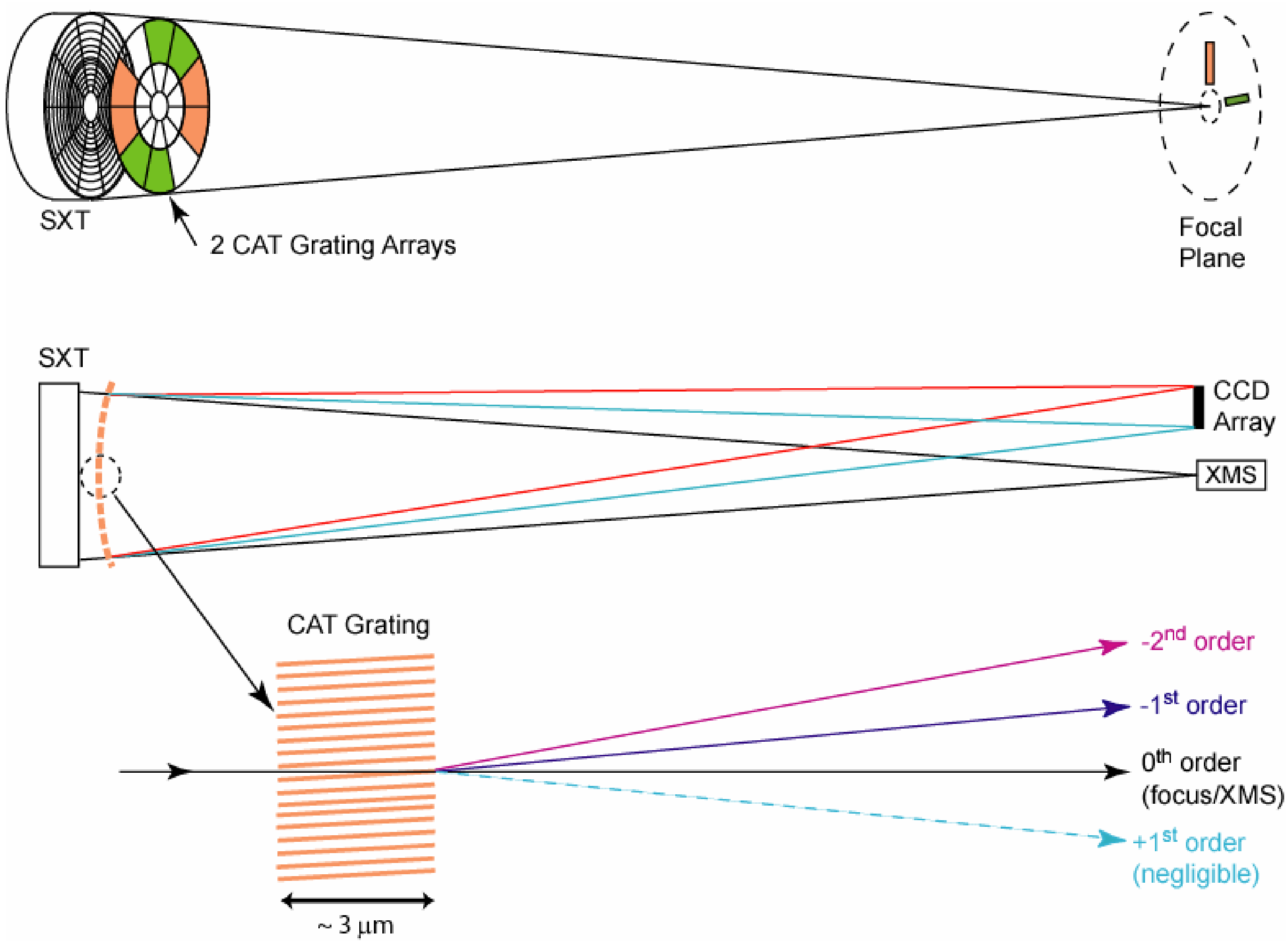
CAT Grating Spectrometer (CATGS)



Instrument is fixed in place and provides data for every observation, without interruption of any other instrument. The observer gets all the data, all the time.

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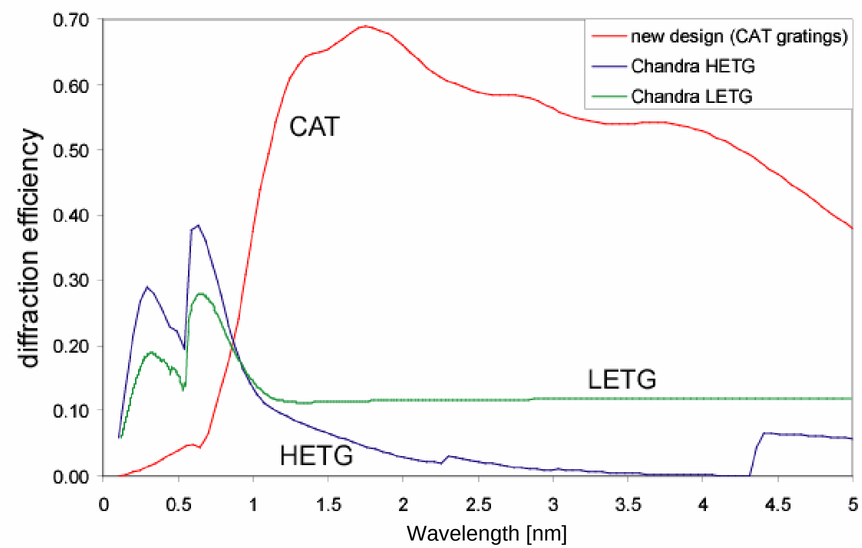
Comparison of Grating Efficiencies:

Chandra versus CAT Grating

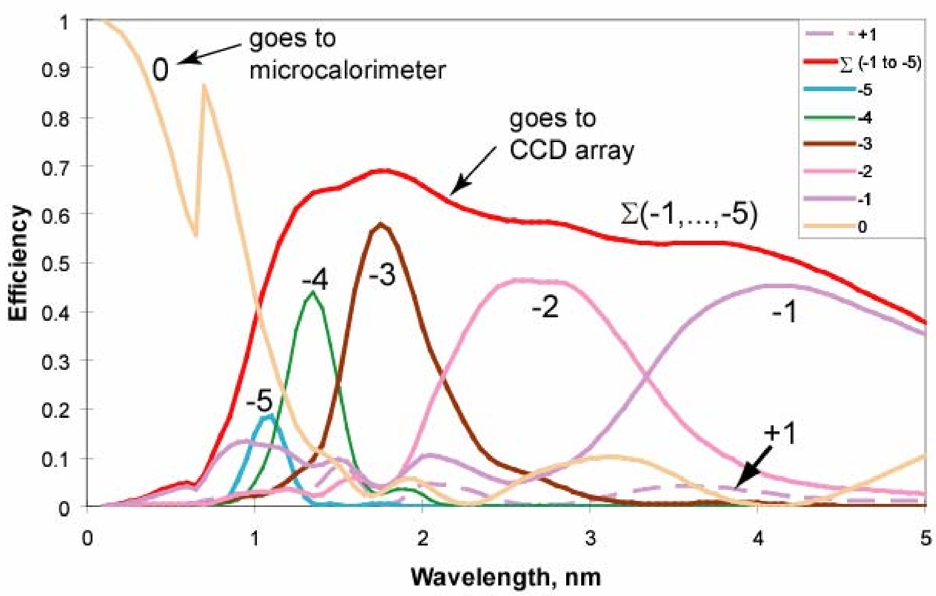


Predicted Silicon CAT Grating Diffraction Efficiency:

- Pronounced blazing

- High efficiency in 1st - 5th order: broad bandpass

- Little loss in 0th order (calorimeter) at shorter wavelengths



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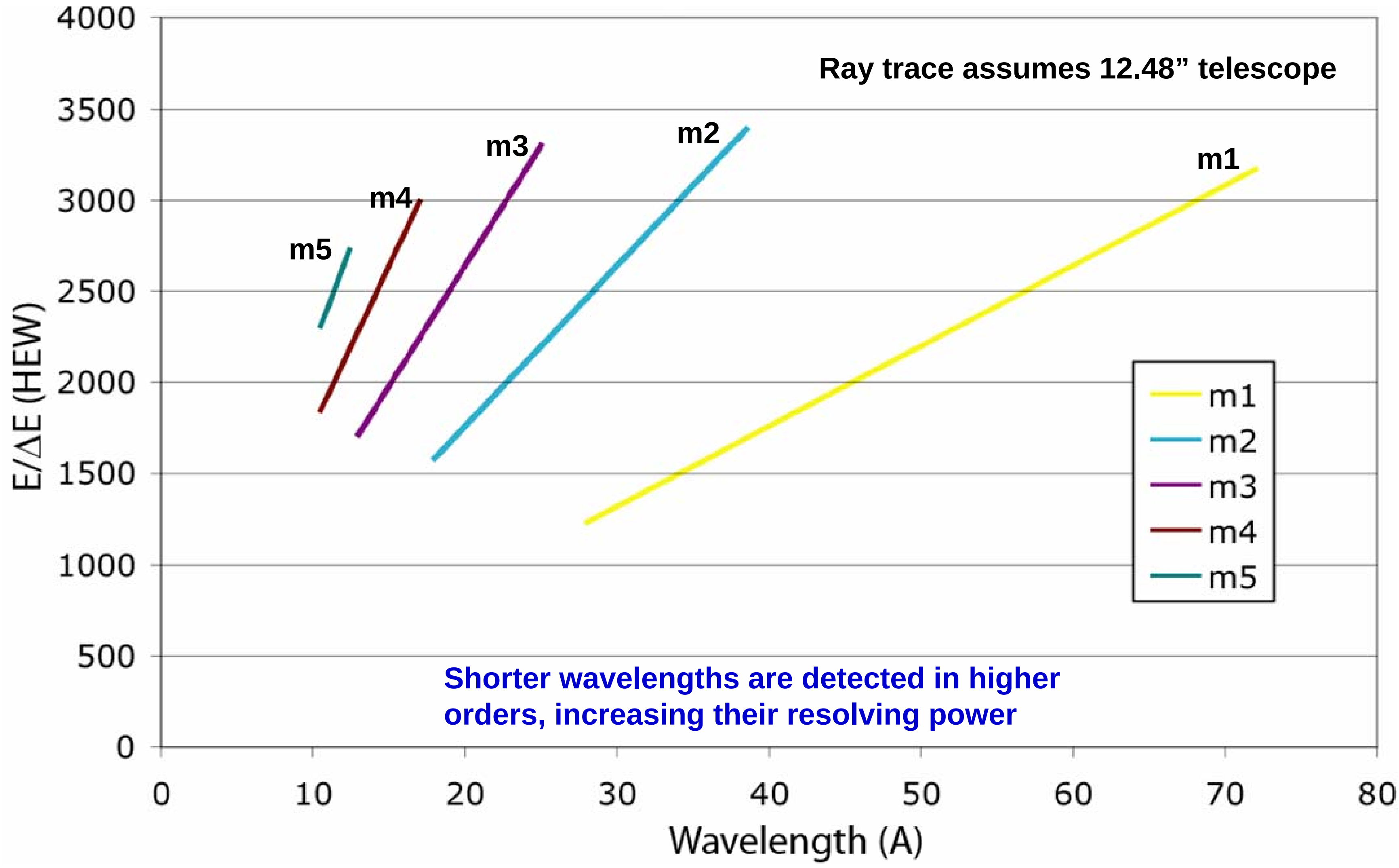
Resolving Powers for Each Order

(where diffraction efficiency > 10%)



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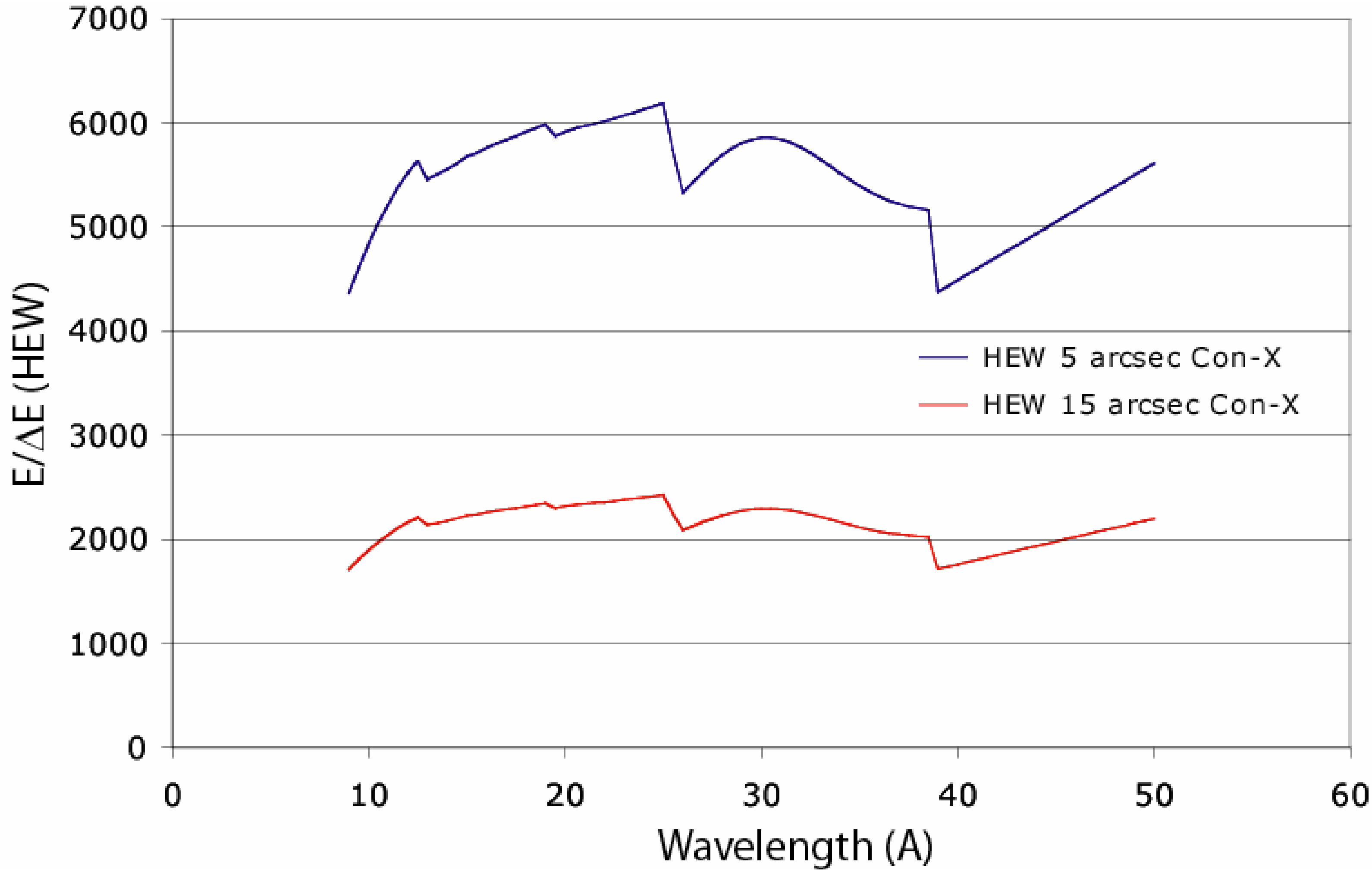
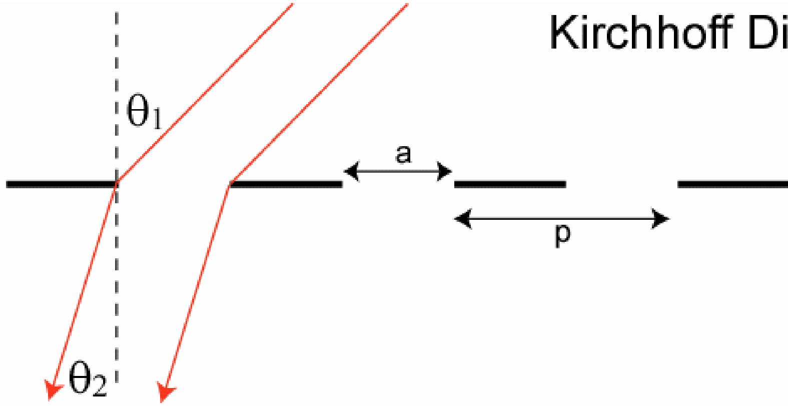
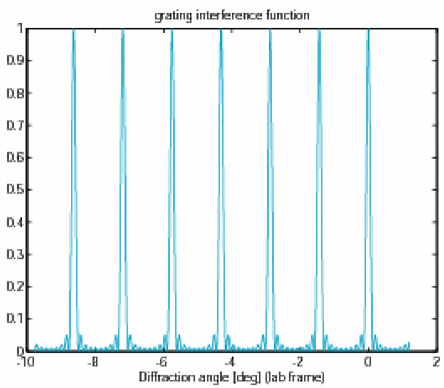
Efficiency-Weighted Resolving Powers (HEW)



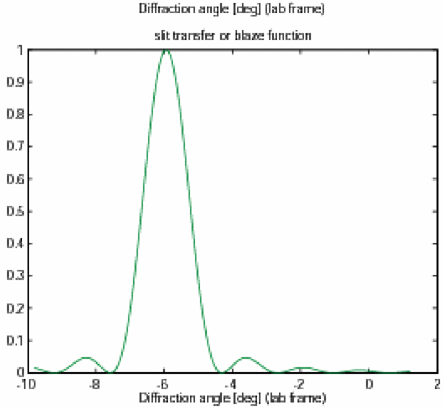
Kirchhoff Diffraction Theory (Born & Wolf)



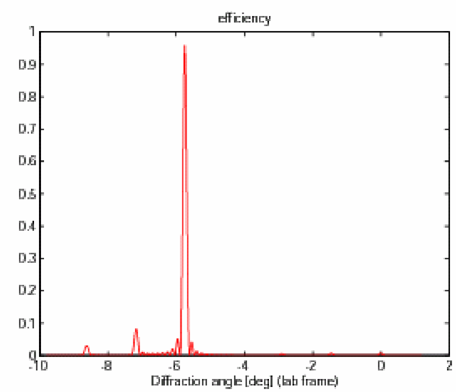
$g = (\pi/\lambda)\, p\, (\sin\theta_2 - \sin\theta_1)$,
$f = (\pi/\lambda)\, a\, (\sin\theta_2 - \sin\theta_1)$,
n = number of slits



$$I_{grat} = (\sin(ng)/n \sin(g))^2$$



$$I_{slit} = (\sin(f)/f)^2$$

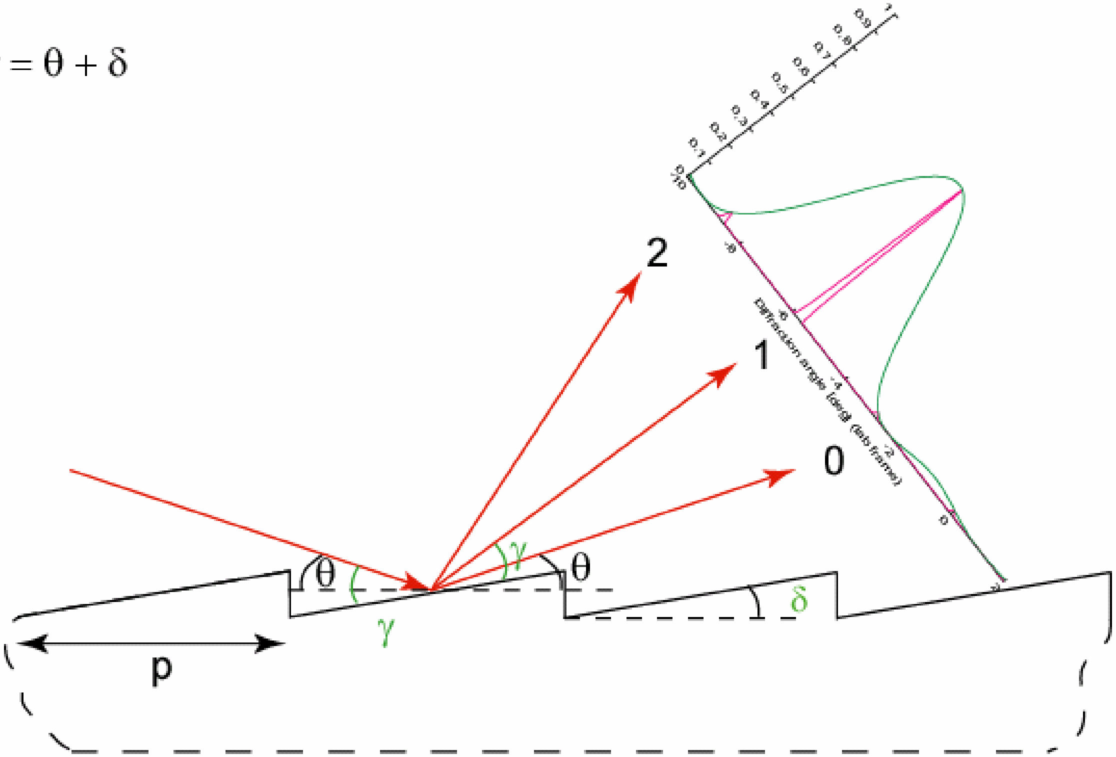


$$I_{total} = I_{grat}\, I_{slit}$$

Blazed Reflection Grating

θ – grazing angle of incidence relative to average grating surface
γ – grazing angle of incidence relative to surface of single grating facet
δ – angle of facet relative to average grating surface

$\gamma = \theta + \delta$



Diffraction angles β_m:

$m\lambda/p = \cos\theta - \cos\beta_m$

Diffraction intensities:

$G(\lambda,p,\theta,\beta) * S(\lambda,a,\theta,\beta,\delta)$

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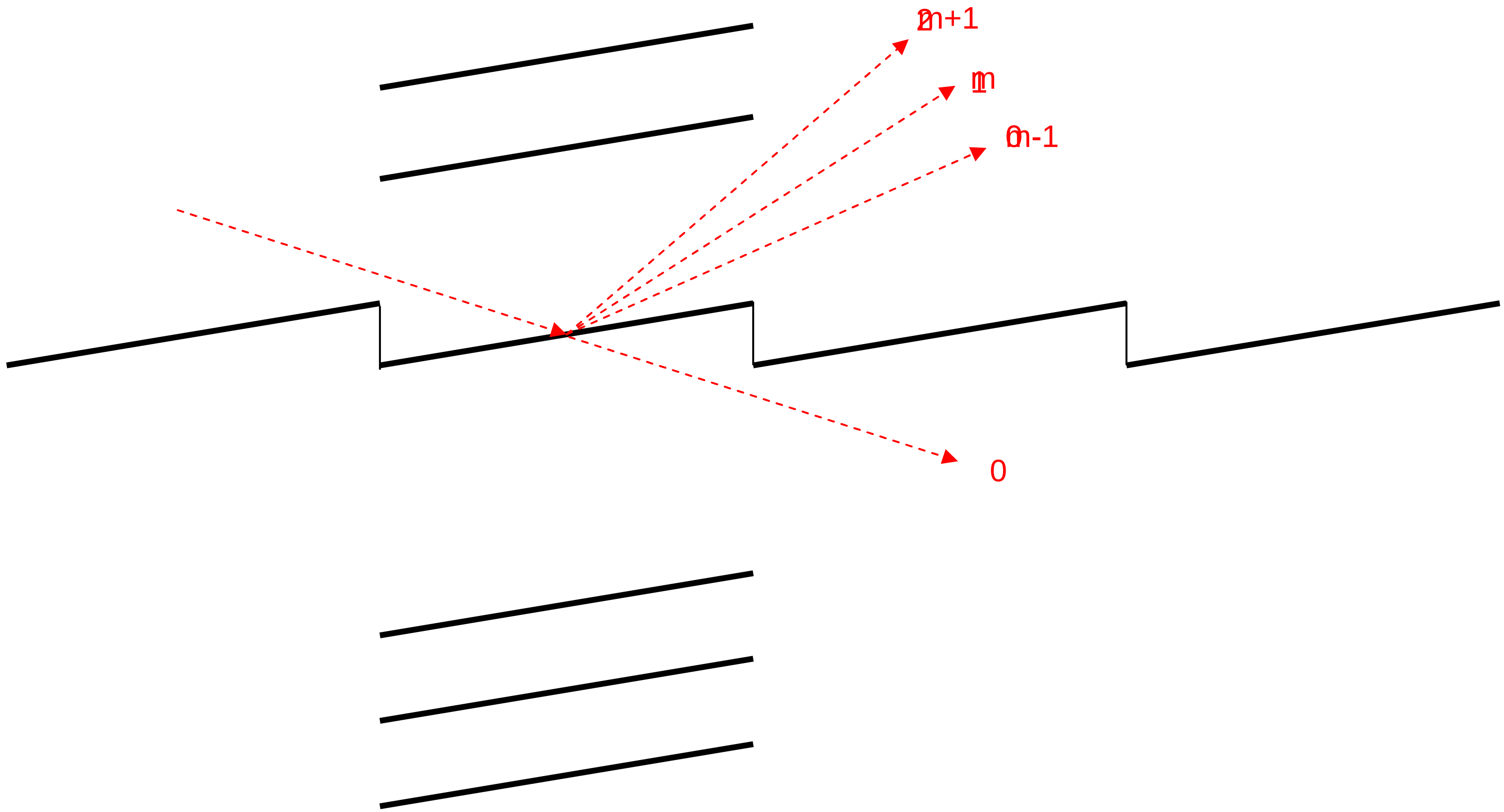
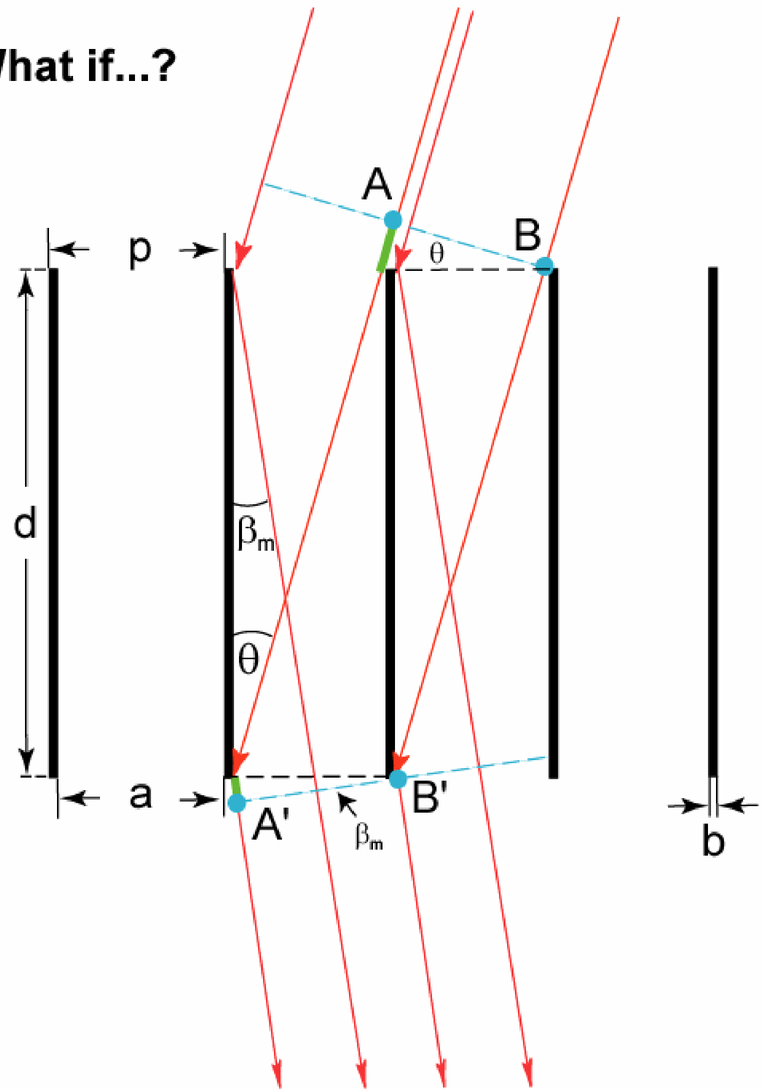
How do you go from a blazed reflection grating to a blazed transmission grating?



What if...?



<u>Constructive interference</u> when path length difference (PLD) between A' and B'

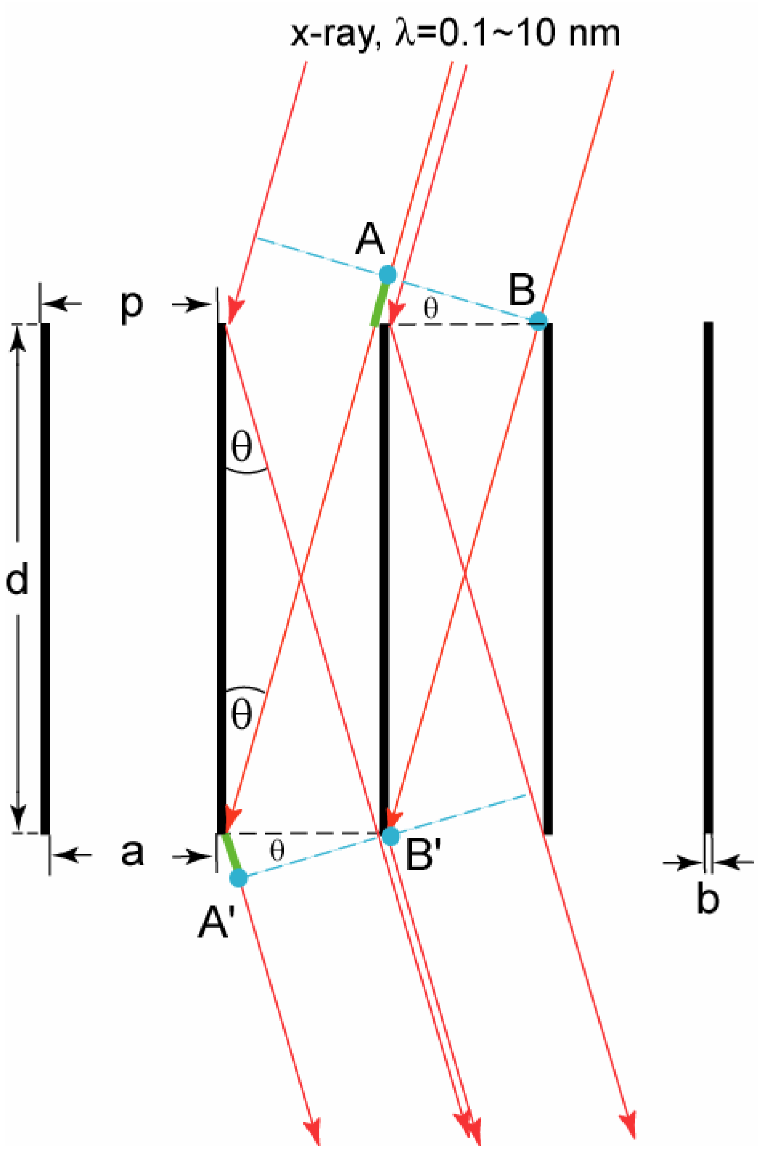
PLD = p sin(θ) + p sin(β_m) = m λ

identical to <u>Grating equation</u>:

$m\,\lambda = p\,(\sin(\theta) + \sin(\beta_m))$,

with m = diffraction order

Critical Angle Transmission (CAT) Grating



Constructive interference when:
path length difference (PLD)
between A' and B'

PLD = 2 *p* sin(θ) = m λ

Blazing: high diffraction efficiency when diffracted order coincides with specular reflection off of grating facet

Refractive index and critical angle for x-ray and EUV :

$n=1-\delta+i\beta,\ \delta<<1,\ \beta<<1,\ \beta\neq0$

$\theta_c=(2\delta)^{1/2}$: ~1 ~ 2°

High reflectivity when:

$\theta < \theta_c$, total external reflection

⇨ **Critical-Angle Transmission (CAT) Grating**

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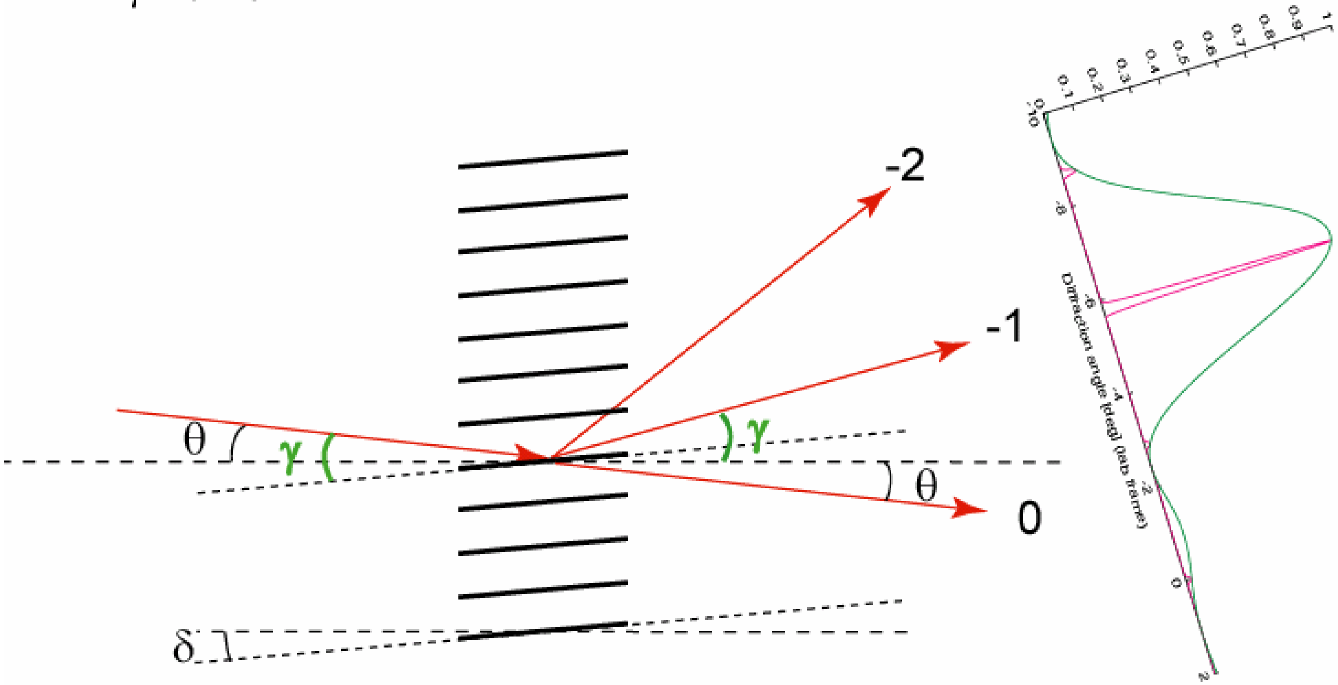
Blazed Transmission Grating

θ – angle of incidence relative to grating normal
γ – angle of incidence relative to surface of single grating facet (grating bar sidewall)
δ – angle of facet (sidewall) relative to average grating normal

$$\gamma = \theta + \delta$$



Diffraction angles β_m:

$$m\lambda/p = \sin\theta + \sin\beta_m$$

Diffraction intensities:

$$G(\lambda,p,\theta,\beta) \star S(\lambda,a,\theta,\beta,\delta)$$

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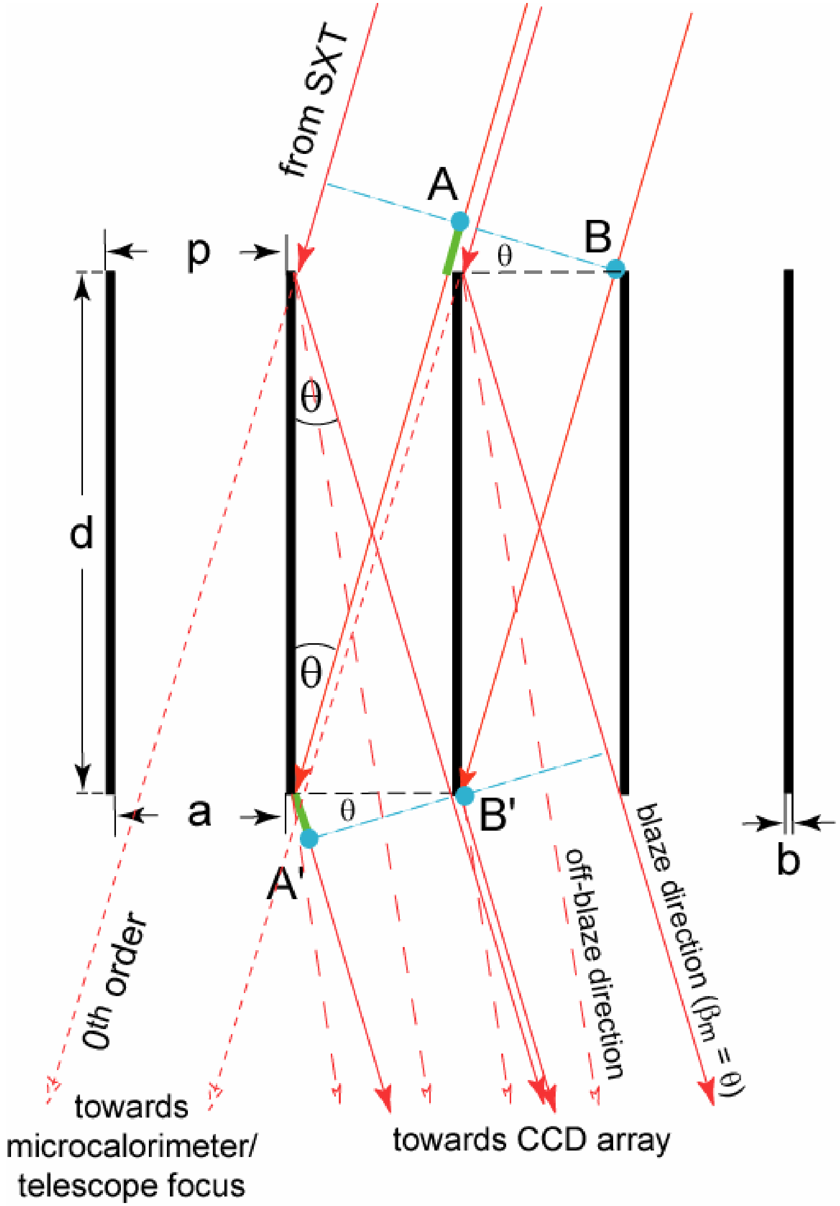
Critical-Angle Transmission (CAT) Grating



The CAT grating is a transmission grating, NOT a reflection grating!

0^{th} transmitted order (PLD = 0) consists of photons that are not deflected but penetrate the grating bars and go to the telescope focus. There is NO 0^{th} order in the direction of specular reflection.

Diffraction is enhanced in the m^{th} order for wavelengths where β_m is close to θ. Diffraction is strongly suppressed on the other side of the 0^{th} order.

Rotation of the grating around the normal to the plane of incidence by a small angle γ results in a shift of the blaze condition relative to the incident beam by 2γ, while the directions of the diffracted orders change by only $\gamma\, (m\lambda/p)^2 \sim \gamma\, m^2 \mathrm{x} 10^{-3}\text{-}10^{-4}$.

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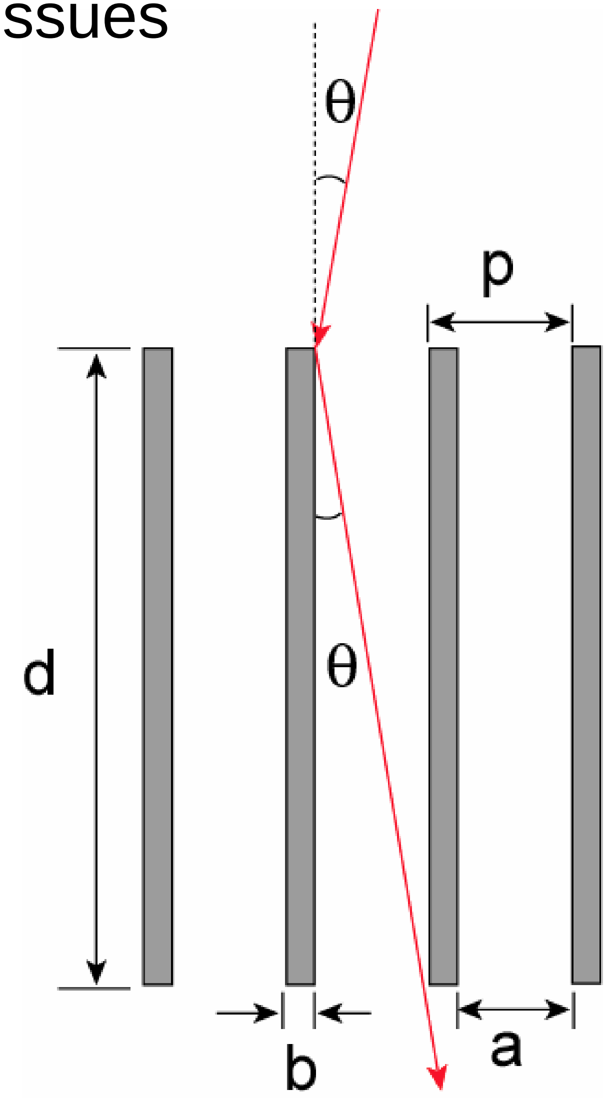
CAT Grating Design Issues

Design Parameters (Con-X)

- Period, p = 100 nm (larger dispersion)
- Duty cycle (b/p) = 0.2 (high throughput)
- Critical angle, θ = 1.5º (high reflectivity)
- d = a/tanθ = 3 µm (optimum “filling”)
- Sidewall roughness < 1 nm (high reflectivity)

Fabrication Challenges

- High aspect ratio (d/b ~ 150)
- Thin grating bars (b = 20 nm)
- Freestanding structure
- Smooth sidewalls (roughness < 1 nm)
- Fine period gratings (p = 100 nm)



Initial prototype: p = 574 nm, d = 10 µm

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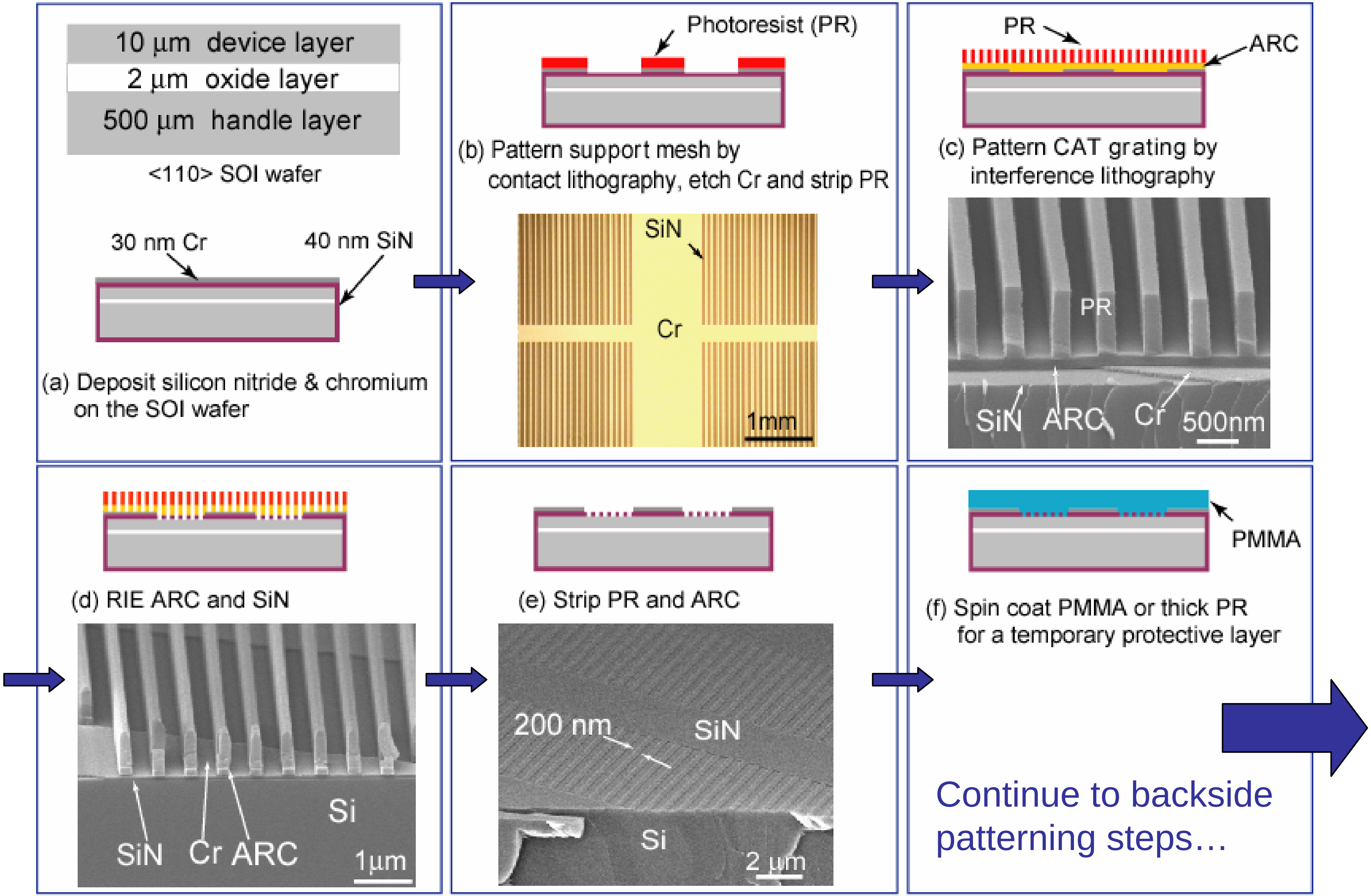
Fabrication Process I. Front Side Patterning



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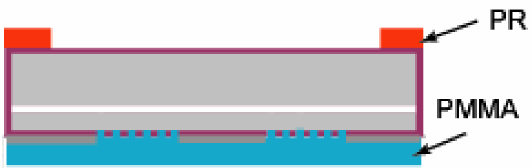
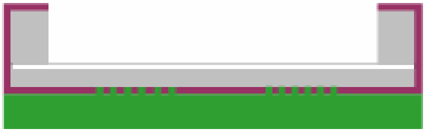
Fabrication Process II. Back Side Patterning



(g) Spin-coat PR on the back & contact lithography

(h) RIE SiN, strip PR and PMMA, and etch Cr

(i) Spin-coat the front with ProTEK*

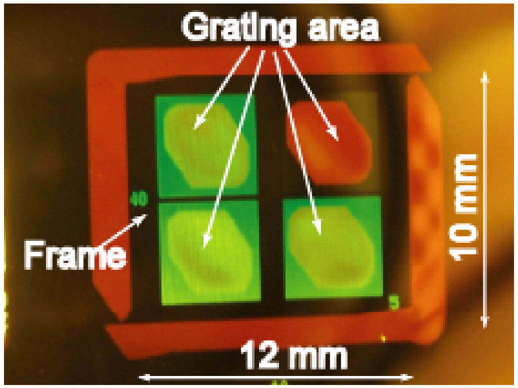


(j) TMAH etch & stop at oxide layer

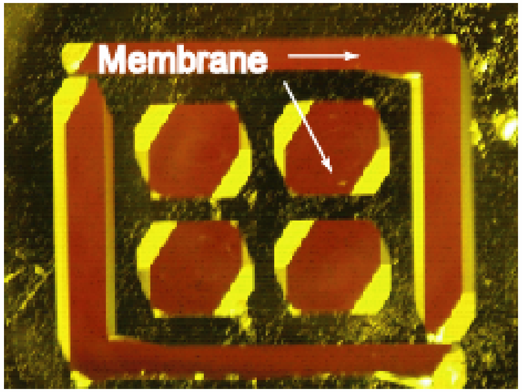
- 6 hours in 25% TMAH @ 90ºC

(k) Remove ProTEK by solvents and short plasma etching

Continue to KOH etching…



Top view

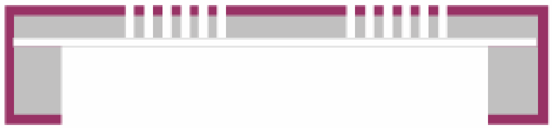


Bottom view

* ProTEK (Brewer Science Inc.) note:

- Protective polymer layer for base solutions such as KOH and TMAH
- ~10 hours in 35% KOH at 80ºC
- Spin-coatable :1~12 µm thick
- Easy to remove : Solvent or O_2 plasma

Fabrication Process III. KOH Etching and HF Etching



(l) BHF dip, KOH etch, stopped at buried oxide

- High KOH concentration: 50 wt%
- Low temperature: 50 ºC
- Etch rates: $R_{<110>} \approx 185$ nm/min
  $R_{<111>} \approx 1.49$ nm/min
- Anisotropy ($R_{<110>}/R_{<111>}$) =124

(m) HF etch buried oxide and SiN mask

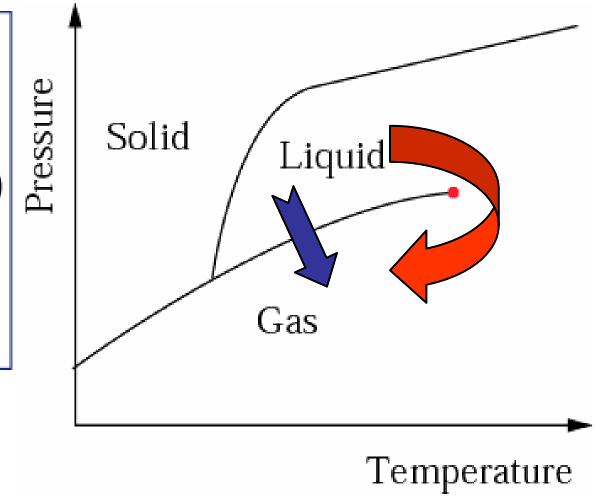
- 5 min in 48 % HF
- Membrane ripples (SiO_2 stress) disappear

Continue to drying step…

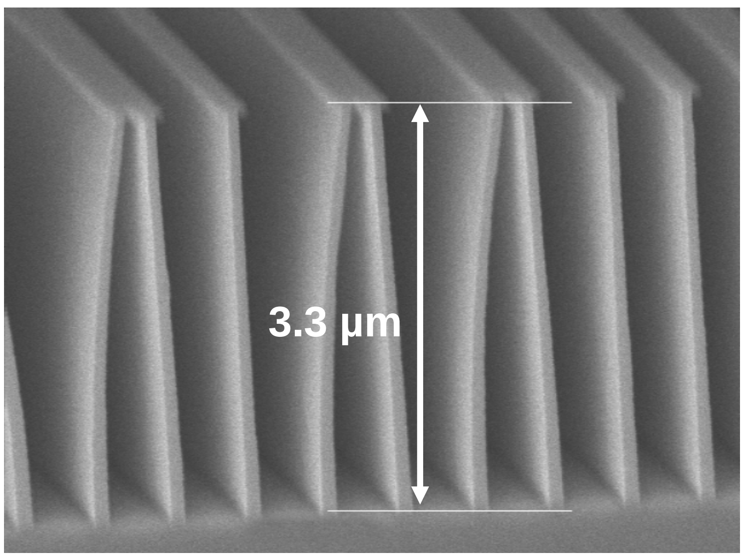
Fabrication Process IV. Supercritical Drying

(n) Dehydration with pure ethanol (miscible with liquid CO_2) and supercritical point drying with liquid CO_2

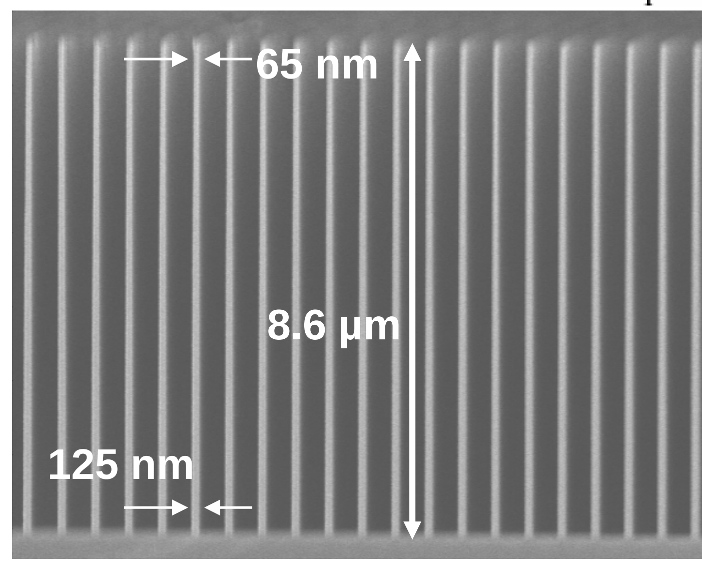
End of process !



- Stiction problem for high aspect ratio structures



Air dried, aspect ratio ~ 20



Supercritical drying, aspect ratio ~ 100

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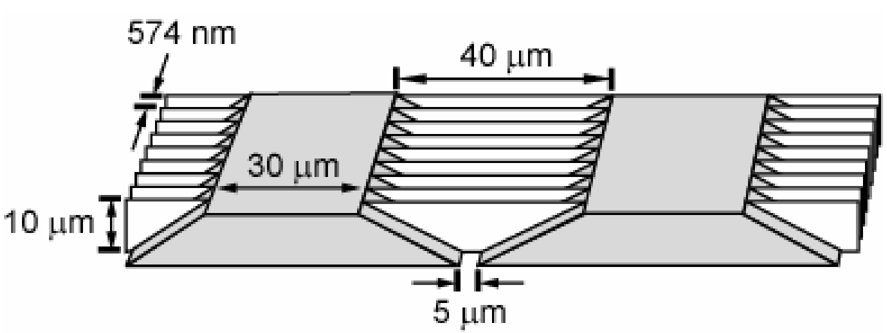
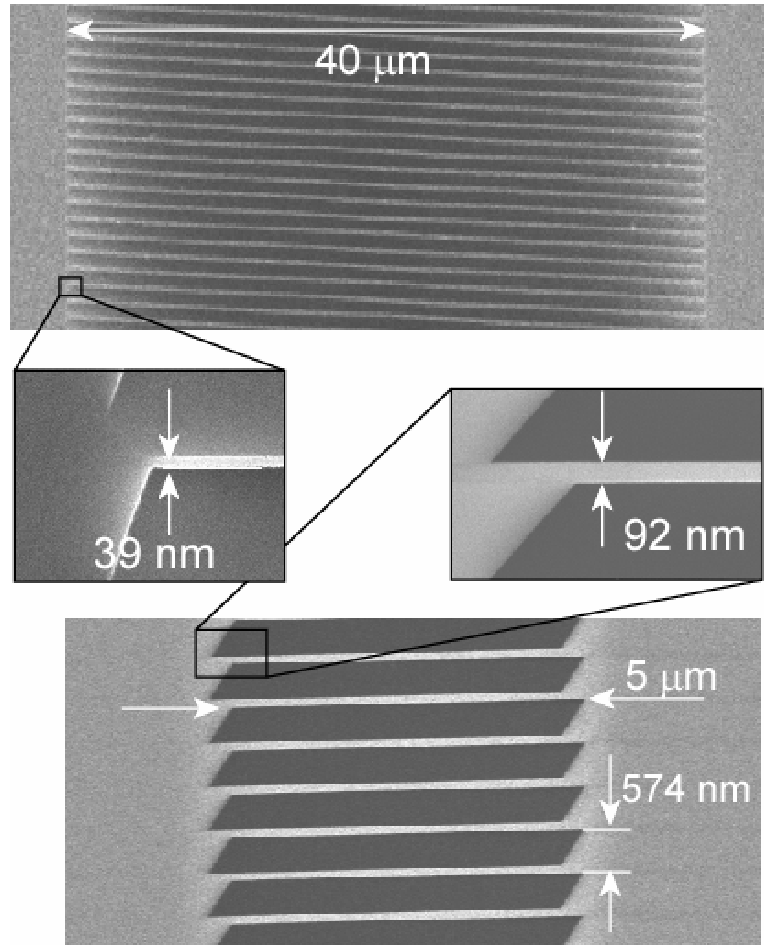
Critical Angle Transmission (CAT) Grating Prototype

Period p = 574 nm
Depth d = 10 μm
Duty cycle (b/p) = 0.15
Aspect ratio (d/b) > 115

Support bar width = 30 μm
Support period = 70 μm

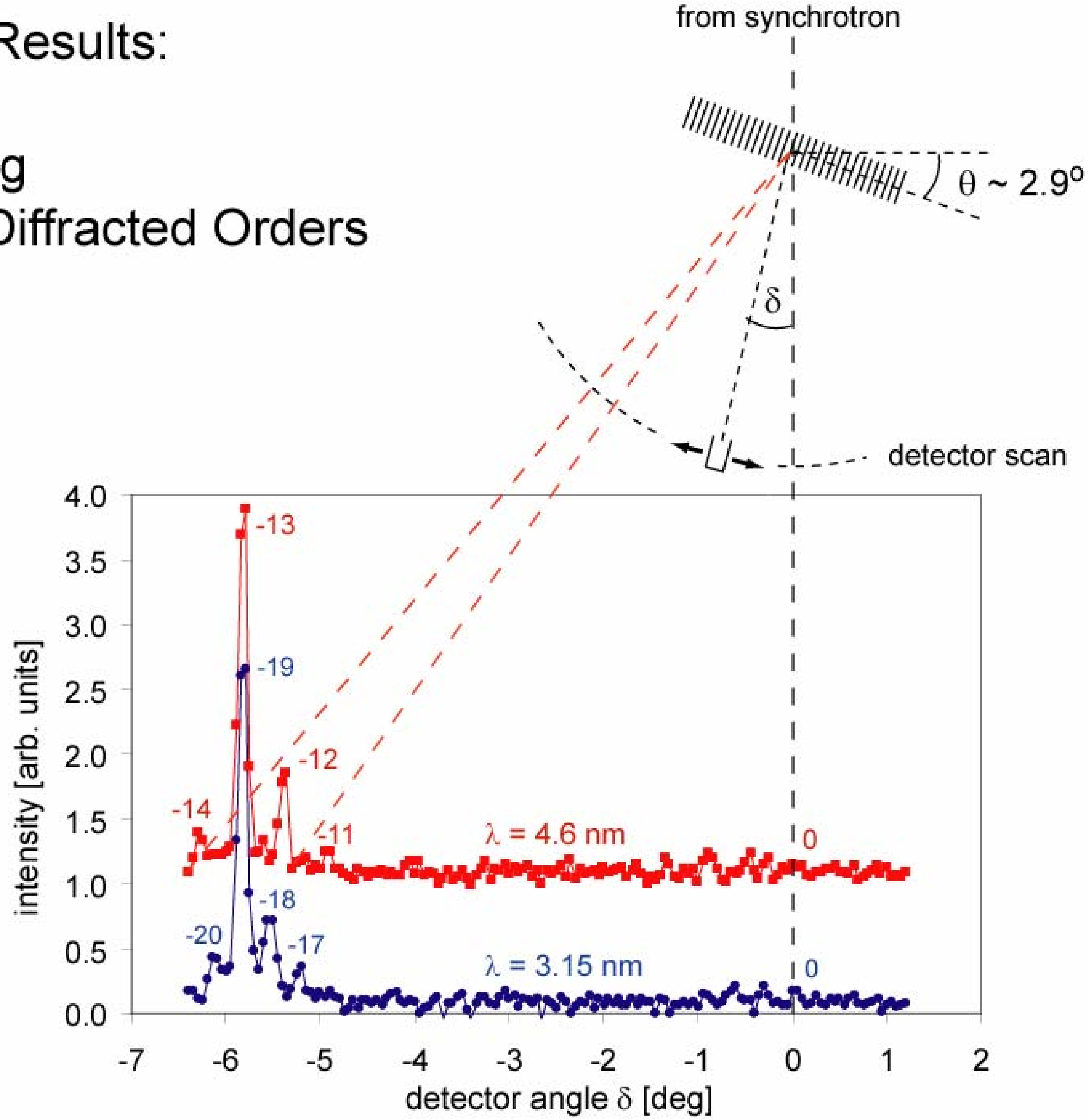




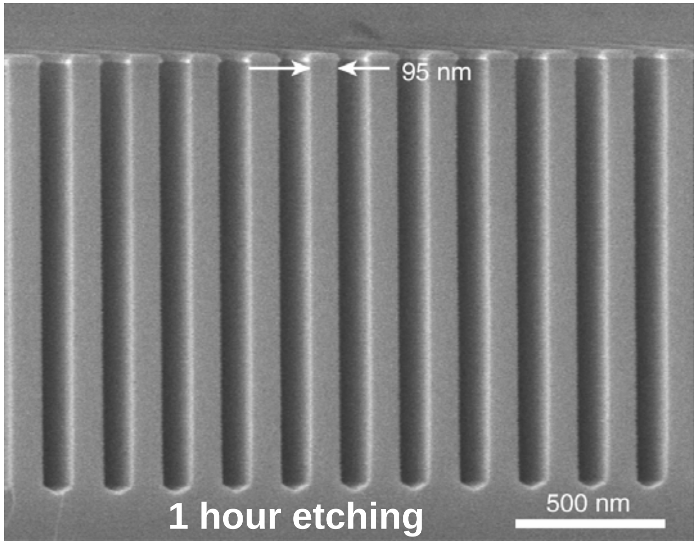
Ahn *et al*., JVST B **25**, 2593 (2007)

X-Ray Results:

- Blazing
- High Diffracted Orders



200 nm-period CAT grating fabrication with improved process



<110> vertical etch rate = 1.4 μm/hr

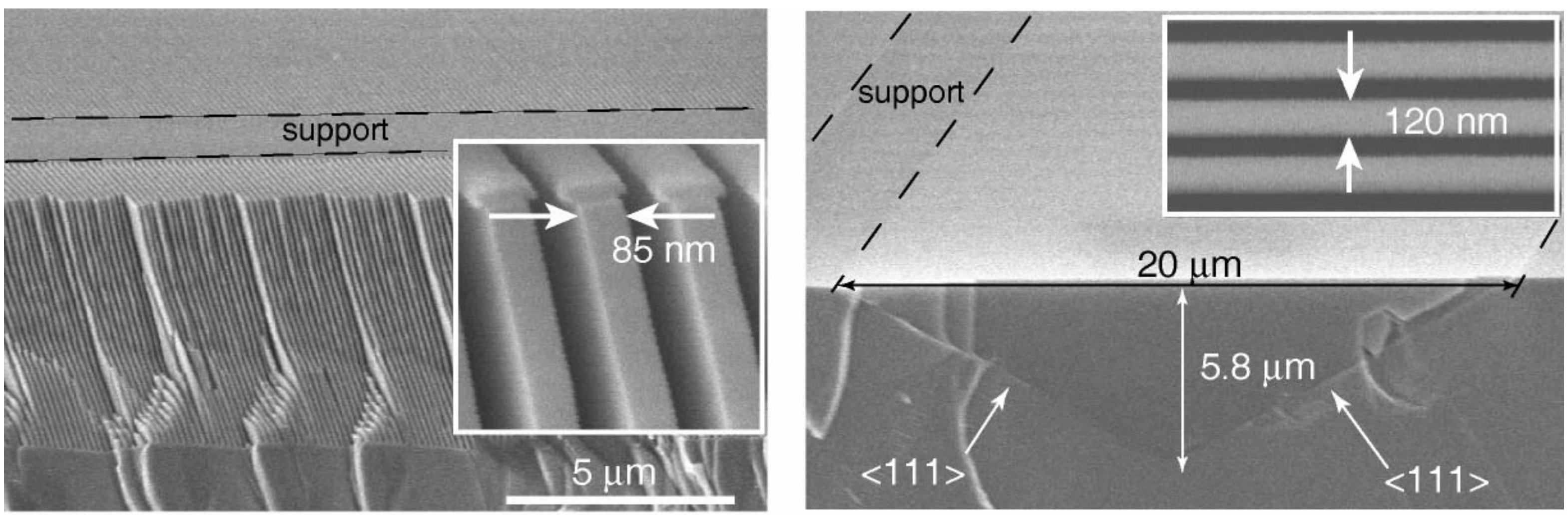
<111> lateral etch rate = 1.25 nm/hr

Record Etch Anisotropy

$(R_{<110>} / R_{<111>})$ = 500 ~ 1000 (!!!)

allows long over-etching ⇒

increased process latitude & uniformity



(a) (b)

5 hour etching and critical point dried

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Summary

- Transmission Grating Spectrometer with Critical-Angle Transmission (CAT) gratings meets/exceeds all Con-X mission requirements.
- Fabricated freestanding CAT grating prototype that meets milestones for aspect ratio, duty cycle, and sidewall roughness.
- Experimentally demonstrated CAT grating principle of operation in the EUV and soft x-ray band with high diffraction efficiency.
- Introduced numerous fabrication process improvements.
- Fabrication of 200 nm-period CAT gratings near completion.
- Next:
  - X-ray tests of 200 nm-period CAT gratings.
  - Increase open area fraction.
  - Develop and optimize integrated support mesh and back-side support for increased mechanical strength and larger grating areas.

Acknowledgments

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- MIT Nanostructures Laboratory

- MIT Microsystems Technology Laboratory